

JRC TECHNICAL REPORTS



Preliminary exploratory impact assessment of short-lived pollutants over the Danube Basin

*An analysis of the year 2010
HTAP V2 emission scenario
with the TM5-FASST tool*

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2015

Report EUR 27068 EN

European Commission
Joint Research Centre
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JRC94208

EUR 27068 EN

ISBN 978-92-79-45064-8 (PDF)

ISSN 1831-9424 (online)

doi:10.2788/6207

Luxembourg: Publications Office of the European Union, 2015

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Abstract

This report is presented as deliverable D2.3 of work package 2 of the Danube Air Nexus. It presents the results of an exploratory impact assessment of short-lived air pollutant emissions on human health, crop production and near-term climate with a focus on the Danube basin. We use a global reduced-form source receptor air quality model TMS-FASST and a recent global pollutant emission inventory (HTAP V2, 2014) to make an attribution by sector of the various impacts and to explore the challenges and opportunities for possible. Preliminary results show that trans-boundary pollution is significantly contributing to population exposure to PM_{2.5} in the Danube area. Dominating polluting sectors are residential sector and agriculture. We estimate that annually 170000 premature mortalities can be attributed to PM_{2.5} pollution in the Danube area, and annual crop losses add up to an economic value of nearly 1 billion US\$. This analysis is a first step in a more detailed, country-wise analysis that will be carried out as a follow-up of this report, with an improved version of the model and specifically designed scenarios for the Danube Basin.

Introduction

Parts of the Danube region, particularly the large cities, are influenced by relatively high levels of air pollutants. Extensive coal and wood burning in some parts of the region is a cause of air pollution, but also other sectors are contributing significantly. Further, air pollution is a trans-boundary problem with emissions in neighbouring countries affecting the air quality levels of downwind regions.

In this report we use the TM5-FASST global air quality model to analyse in an exploratory way the impacts of air pollutants on human health, air quality and agriculture. We use the available, in-house developed, emission inventory for the year 2010 which contains country-wise pollutant emissions segregated by sector, as input to the TM5-FASST, to obtain an estimate of the attribution by sector to population-weighted PM_{2.5} exposure by country (or group of countries), and to evaluate crop losses from ozone pollution. Although the TM5-FASST model does not provide detailed city-level exposure information, the over-all country-averaged attribution gives already a useful indication on which sectors are dominating the pollution levels, and how much of the country-averaged pollution is generated by internal or by imported pollution from other countries.

The TM5-FASST model

JRC-IES has developed the reduced-form global air quality source-receptor model (AQ-SRM) TM5-FASST. In general, AQ-SRMs link emissions of pollutants in a given source region with downwind impacts, using knowledge of meteorology and atmospheric chemistry. The source region is any point or area from which emissions are considered; the receptor is any point or area at which the pollutant concentration and impact is to be evaluated. Pollutants can be primary (or passive): they do not undergo chemical transformation during their atmospheric lifetime and are only affected by dry and wet removal from the atmosphere (e.g. elemental carbon, mineral dust), or they can be secondary, in which case the emitted compound is transformed in one or more secondary components, e.g. NO₂ forms nitrate aerosol but also leads to the formation of O₃; emitted SO₂ is transformed into sulphate aerosols as secondary product. Another type of secondary effect is when emitted compounds indirectly affect the chemical formation of other secondary species, e.g. NO₂ has a (small) influence on the formation rate of SO₄ from SO₂. In summary, a specific secondary 'end product' can be formed from 1 or more emitted precursors, and an emitted precursor will lead to 1 or more end products (see Table 1). An AQ-SRM will then include a functional relation between each emitted precursor and each end product for each source region and each receptor region.

TM5-FASST is a reduced-form SRM: the relation between the emissions of compound i from source x and resulting pollutant j concentration (where $j = i$ in case of a primary component) at receptor y is expressed by a simple functional relation which mimics the

underlying meteorological and chemical processes. In the current version of TM5-FASST, the function is a simple linear relation:

$$C_{i \rightarrow j, y, x} = C_0 + A_{i \rightarrow j, x, y} E_{i, x}$$

where $C_{i \rightarrow j, y, x}$ is the concentration of species j at receptor y formed from precursor i emitted at source x , $E_{i, x}$ is the emission rate (kg/yr) of precursor i at source x , $A_{i \rightarrow j, x, y}$ is the so-called source-receptor coefficient (SRC) between source location x and receptor location y for emitted precursor i leading to end product j , and C_0 is a constant.

The source-receptor coefficients are stored as matrices with dimension $[x, y]$. A single matrix is available for each precursor and for each resulting component from that precursor. The SRCs have been derived from a set of runs with the full chemical transport model TM5-CTM (Krol et al., 2005) by performing a set of emission perturbation runs relative to a base run for each of a defined set of source regions and precursor components. TM5-CTM explicitly solves the mass balance equations of the species using detailed meteorological fields and sophisticated physical and chemical process schemes. TM5-CTM covers the global domain with a resolution of $1^\circ \times 1^\circ$. More in particular, the applied procedure to calculate the SRCs was the following:

- 56 source regions were defined (see Figure 1) covering the global continents.
- A base run with a reference global emission dataset for all relevant pollutant and pollutants precursors for the year 2000 was performed, including SO_2 , NO_x , BC, OC, NMVOC, and NH_3 . This base run produces the resulting base concentrations of all relevant pollutants at a global $1^\circ \times 1^\circ$ resolution.
- A series of perturbation runs were performed, where sequentially in each of the defined 56 source regions, the emissions of each of the pollutant precursors was reduced over the entire source region by 20% relative to the base run, and the resulting concentration of all affected pollutant species was calculated, in the same way as it was done for the base run. The difference between the concentration field for a specific compound from each perturbation run and the base run is a global 360×180 concentration field ($1^\circ \times 1^\circ$ resolution), the so-called delta-field. Figure 2 shows a typical delta-field of SO_4 for a 20% perturbation of SO_2 emissions in India. Additional to the 56 continental source regions, separate perturbation runs were performed for aggregated international shipping emissions (occurring over the oceans) and for aviation, so that in total 58 source 'regions' are available. In the following, the source categories shipping and aviation are included in the term 'source regions' unless otherwise mentioned.

Hence, the total concentration of component j in receptor region y , resulting from arbitrary emissions $E_i(x)$ of *all* its precursors i at *all* source regions x is obtained by overlaying emission-scaled delta fields $\Delta C_{i \rightarrow j, x, y}$ for all source regions:

$$C_{i \rightarrow j}(y) = C_{j, base}(y) + \sum_x \sum_i \Delta C_{i \rightarrow j, x, y} \cdot \left[\frac{E_i(x) - E_{i, base}(x)}{0.2 E_{i, base}(x)} \right]$$

In the case of $j=\text{ozone}$, the i precursors would comprise $[\text{NO}_x, \text{NMVOC}, \text{CO}, \text{CH}_4]$. An overview of all considered precursor-pollutant combinations are given in Table 1. This set of linear equations for all components and all source and receptor regions emulates the full-fledged TM5-CTM, and constitutes the ‘kernel’ of TM5-FASST

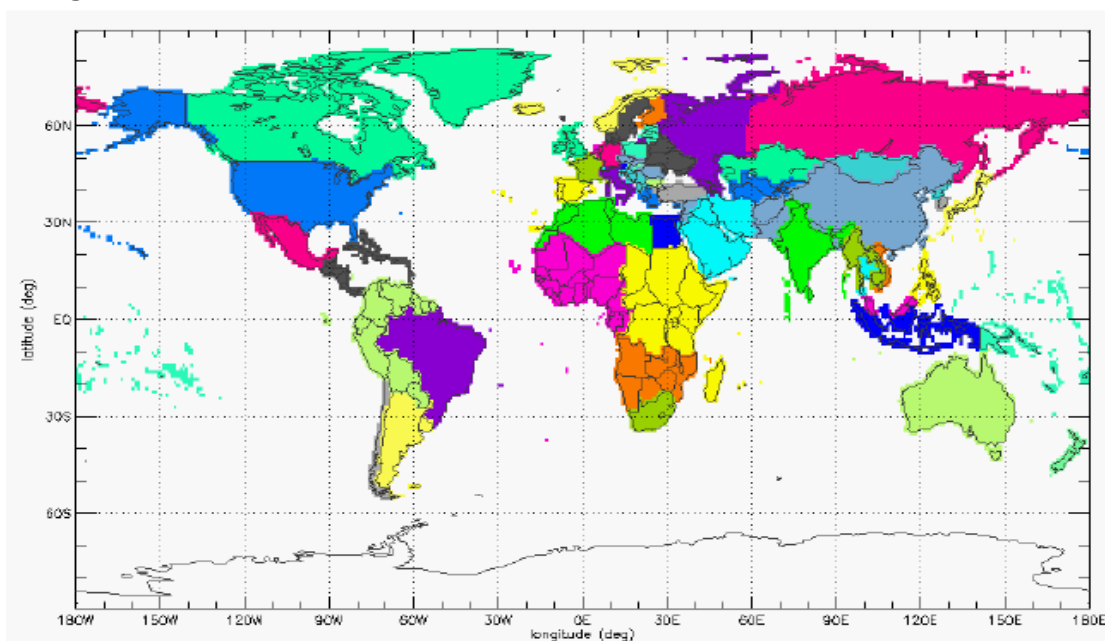


Figure 1: Map of the TM5-FASST emission source regions

The delta fields are stored at the native $1^\circ \times 1^\circ$ resolution of the TM5-CTM model and in principle the individual grid cells can be aggregated into any customized receptor region. One particularly useful aggregation scheme is to combine the receptor grids into the 56 defined continental source regions (open oceans and aviation space are not considered as receptor region); hence the SRCs are stored into 58×56 matrices between 56 identical continental source and receptor regions, plus shipping and aviation as sources. These matrices have been implemented in an Excel version of the TM5-FASST tool, which was used for this assessment.

The resulting air pollutant concentrations, and their specific spatial distribution, are then further processed into impacts, such as the effect of $\text{PM}_{2.5}$ on human health (mortalities, reduction of statistical life expectancy), the impact of O_3 on vegetation and crop damage, the deposition of eutrophying or acidifying components to sensitive ecosystems. Mostly these calculations are based on simple empirical dose-response functions (see section below), but they require additional data to be overlaid with the pollutant concentration (or derived metric) in order to properly calculate the exposure (population maps, crops and vegetation maps, sensitive ecosystem maps, ...). In order to provide correct exposure estimates, the pollutant concentration SRCs have been population-weighted when aggregating from $1^\circ \times 1^\circ$ resolution to the 56 receptor regions.

Apart from air pollutant concentrations as end points, a specific set of SRCs has been calculated to evaluate the *global* radiative forcing resulting from the emitted components. In this case, unlike the pollutant concentrations, the relevant receptor

region is the globe, hence the SR matrix is a 58x1 array. The global radiative forcing can be further processed into other climate-relevant metrics, like equivalent CO₂ emissions and global temperature change. These features are included in TM5-FASST as well.

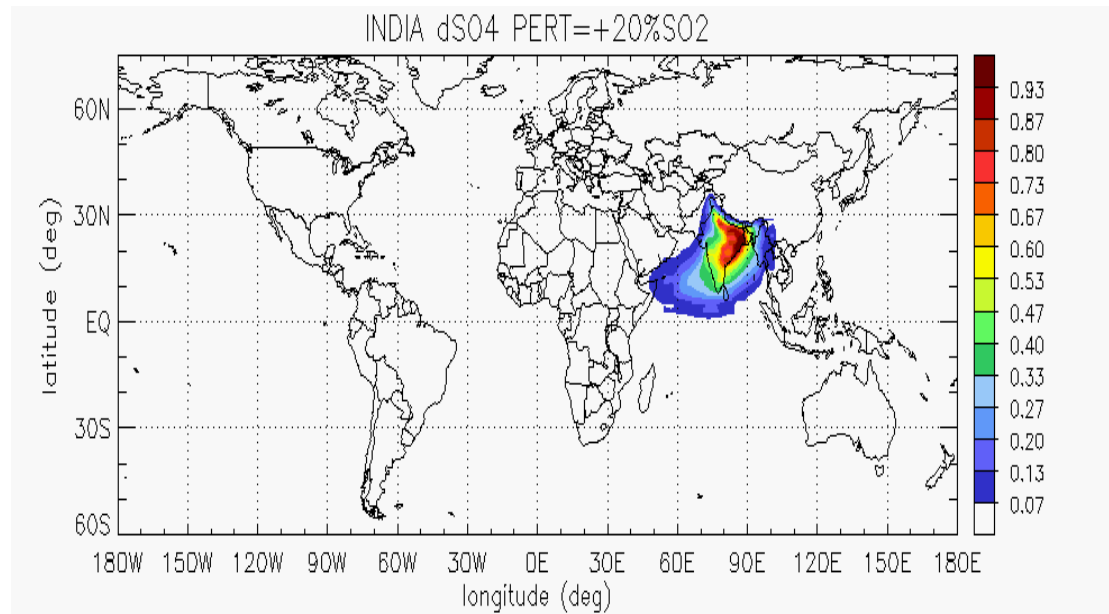


Figure 2: change in SO₄ concentrations (μg/m³) at the surface following a +20% SO₂ emission increase in India

Table 1: Relevant emitted precursor-pollutant pairs. The number of x's gives a qualitative indication of the most influential precursors (xxx: highest influence). Influences indicated by 1 x are due to feedback mechanisms affecting the level of oxidants, and hence the lifetime of OH radicals, in the atmosphere, which in turn affects the oxidation rate of the precursors.

Pollutant→ Precursor↓	SO ₂ gas	NO _x gas	NH ₃ gas	O ₃ gas	CH ₄ gas	SO ₄ pm	NO ₃ pm	NH ₄ pm	BC pm	POM pm	SO _x dep	NO _y dep	BC dep
SO ₂ (g)	xxx	x	xx	x	x	xxx	xx	x x			xxx		
NO _x (g)	x	xxx	xx	xxx	xx	xx	xxx	x x			x	xxx	
NH ₃ (g)	x	x	xxx	x	x	xx	xx	x xx			x		
BC (pm)									xxx				xxx
POM (pm)										x xx			
NMVOC (g)	x	x	x	xxx	xx	x	x	x			x		
CO (g)				xxx	xx								
CH ₄ (g)	x	x	x	xx	xxx	x	x	x			x		

Notes: (g) = gaseous component; (pm) = particulate matter; dep = deposited component

The linearization of complex atmospheric processes in TM5-FASST inevitably induces an additional uncertainty in the results, but comparison with the full CTM TM5 model shows acceptable agreement for a wide range of emission scenarios (Leitão et al., 2013).

In particular, performance of the TM5-FASST model deteriorates when strong emission reductions are applied compared to the base run on which the SRCs are based, while for relative emission increments, resulting concentrations show excellent agreement between reduced form and full TM5 model.

For the DANUBE study, we extract from the 56 receptor regions on which the TM5-FASST model is operating, the Danube basin as a receptor region for a set of global emission scenarios. Table 2 shows a list of the (aggregated) TM5-FASST source regions, containing the countries that belong to the larger Danube basin (i.e. an extension of the set of countries through which the Danube is flowing). Because of the way the source regions have been fixed at the time of the development of the FASST Tool, some source regions may contain countries that do not belong to the Danube region.

Table 2: TM5-FASST regions belonging to the Danube region

TM5-FASST regions, part of Danube Basin	Countries included in region
AUT	Austria, Slovenia, Liechtenstein
CHE	Switzerland
ITA	Italy, Malta, San Marino, Monaco
GER	Germany
BGR	Bulgaria
HUN	Hungary
POL	Poland, Estonia, Latvia, Lithuania
RCEU (Rest of C. Europe)	Serbia, Montenegro, FYR of Macedonia, Albania
RCZ	Czech Republic, Slovakia
ROM	Romania
UKR	Ukraine, Belarus, Moldova

Methodologies for the calculation of the impacts from modelled pollutant concentrations

Health impacts:

Ground-level concentrations of ozone and PM_{2.5} are associated with cardiovascular and respiratory mortality (e.g. Jerrett et al. 2009; Krewski et al. 2009, WHO, 2013). The 2009 report of the World Health Organization estimated that particulate matter exposure causes about 8% of lung cancer deaths, 5% of cardiopulmonary deaths and about 3% of respiratory infection deaths, which is about 1.15 million deaths each year (WHO, 2009). On the other hand, a later study by Anenberg et al. (2010) estimated that global mortalities due to respiratory illness caused by O₃ were about 0.7 million and population exposure to PM_{2.5} resulted in about 3.5 million cardiopulmonary and 0.2 million lung cancer mortalities. In TM5-FASST, the methodology described in the latter study, as well as a more recent revision of the exposure functions (Lim et al., 2013;

Burnett et al., 2014) are applied to determine the outdoor-air-pollution-induced premature mortalities for a population older than 30 years exposed to PM_{2.5} and O₃. Population numbers (age fractions and totals) are obtained from the UN Population Division (UN, 2011). Cause-specific mortalities from ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), lung cancer (LC) and acute lower respiratory illness diseases for children aged below 5 years (ALRI) are calculated with risk rate (RR) functions provided by Burnett et al. (2014) as a function of PM_{2.5} exposure. In the case of exposure to O₃ only mortalities from respiratory disease are considered applying the risk rate from Jerrett et al, 2009, using the risk rate functions described in Anenberg et al. (2010). Cause-specific base mortalities for the year 2005 are taken from the most recent WHO ICD-10 update (WHO, 2012) for individual countries where available, or back-calculated from 14 WHO regional average mortalities when not available.

Crop yield impacts:

Ozone is a toxic compound to plants with considerable negative effects on leaf health, growth and productivity of crops, trees and other plants, affecting the vegetation composition and diversity (e.g., Fuhrer and Achermann, 1994; Jager et al., 1996; Fuhrer, 2009). In fact, O₃ is one of the main air pollutants that reduces crop yields leading to the loss of large amount of wheat, maize and rice (UNEP/WMO, 2011). This loss is not only important in regard to damage in ecosystem but will result in large economic losses and is a threat to food security. The O₃ damage on crops and vegetation with its impact on yield loss is also estimated with TM5-FASST. The methodology applied in TM5-FASST to calculate the impacts on 4 crops (wheat, maize, rice and soy bean) is based on Van Dingenen et al. (2009). In brief, as it was done for the pollutants, the SR-relations for various metrics for crop exposure to ozone (AOT40 and mean seasonal daytime ozone concentration) were pre-calculated based on stored hourly ozone concentrations from the full TM5 base and perturbation model runs. Country or region-averaged values for the O₃ metrics are obtained by averaging or accumulating over the appropriate crop growing area (which varies by crop and geographical location) the SR coefficients, and overlaying those with crop suitability maps from Fischer et al. (2000). Whereas in Van Dingenen et al (2009) crop growing season data were obtained from various sources, we recently updated this part of the data by retrieving globally gridded growing season information as well as geographical crop distribution from the Global Agro-Ecological Zones project (GAeZ, <http://www.fao.org/nr/gaez/en/>). The relative yield loss for each crop is then obtained by applying appropriate exposure-response functions to the region-averaged exposure metric (see Van Dingenen et al, 2009). Currently only 4 crop types are included in the analysis due to limitations on data availability.

Emission inventory

Year 2010 HTAP emission inventory: analysis by sector of PM_{2.5} exposure

The focus of this part is the attribution of PM_{2.5} to the contributing emitting sectors for the regions of interest, with a consistent methodology across all regions, and based on a global up-to-date emission inventory that contains the required sectorial detail. The sector-separated emissions for this study are obtained from the Hemispheric Transport of Air Pollution (HTAP V2) harmonized emissions database for the year 2010 (HTAP-V2, 2014). The HTAP V2 dataset consists of 0.1° x 0.1° emission grid-maps of CH₄, CO, SO₂, NO_x, NMVOC, NH₃, PM₁₀, PM_{2.5}, BC and OC for the years 2008 and 2010 (Maenhout et al., 2012). This dataset uses nationally reported emissions combined with regional scientific inventories in the format of sector-specific grid-maps. The grid-maps are complemented with the Emission Database for Global Atmospheric Research (EDGARv4.3) data for those regions where HTAP V2 data are not available. The global grid-maps result from the cooperation of US-EPA, EPA-Canada, the Model Inter-comparison Study Asia (MICS-Asia group), EMEP/TNO Europe, the Regional Emission inventory for Asia (REAS) and the EDGAR group. The primary objective is to serve the scientific community for hemispheric transport of air pollution.

The HTAP V2 dataset provides total emissions (Kg/Year) by country and activity sector for the year 2010. The main pollutant sectors of interest are:

- **Air** (international and domestic aviation)
- **Shipping** (international shipping)
- **Energy** (power plant industry)
- **Industry** (manufacturing, mining, metal cement, solvent industry)
- **Transport** (ground transport including road, rail, pipeline, inland waterways). All types of fuels are included (including biofuels with short cycle C). Dust does not include re-suspended road dust.
- **Residential** (heating/cooling of buildings and equipment/lighting of buildings and waste treatment)
- **Agriculture** (agriculture but not agricultural waste burning). NH₃ is the main chemical element for this sector.
- **Biomass Burning** (agricultural (FAOSTAT) waste burning and biomass burning from the Global Fire Emissions Database, version 3 (GFED3, (van der Werf et al., 2010)).

For the purpose of the TM5-FASST study, high-resolution emissions for SO₂, NO_x, BC, OC, NH₃, and primary PM_{2.5}, for each sector (except shipping and aviation which are treated as separate source 'regions'), were aggregated for each of the defined 56 TM5 FASST regions. Having the individual sector emissions available, we use this information in the first place to derive the attribution by sector in resulting PM_{2.5} for the year 2010 with the TM5-FASST model, with a focus on the DANUBE basin, in order

to get a better understanding of the relative contribution of the different pollutant emission categories.

Results

Year 2010 - PM2.5 and attribution by sector

Figure 3 shows the year 2010 annual mean anthropogenic PM2.5 concentrations (population weighted average) for the selected regions that are part of the DANUBE basin. Concentrations range between 10 and 18 $\mu\text{g}/\text{m}^3$. These values are conservative estimates because they are based on 100x100km² grid size population weighting, and because the natural components of PM2.5 (mineral dust and sea-salt), as well as transport-driven re-suspended road dust are not included. Further, agricultural emissions contain only NH₃ (as precursor for the secondary PM2.5 components ammonium nitrate and sulphate) but no primary emissions, and secondary organic PM2.5, both from biogenic and anthropogenic origin is not included either. It should be noted however that these region-wide PM2.5 averages include rural background concentrations in rural populated areas and cannot be directly confronted with annual means of point measurements in urban or urban background stations which are usually reported to illustrate air pollution issues.

The figure also shows for each of the main emission source categories their respective share in the PM2.5 concentration. Further, in both panels we show the portion of total and sector-segregated PM2.5 that can be attributed to emissions inside each region ("domestic" emissions, labelled DOM) and emissions outside the regions (labelled EXT). The in-region generated PM2.5 fractions and the percentages of each contributing sector are given in Table 3. Imported PM2.5 pollution can be as high as 70% (Hungary). Obviously the fraction depends on the size of the region and the vicinity of neighbouring polluting regions. This explains also the high 'domestic' pollution for Italy. The residential sector appears to be the dominant sector in most of the regions. Agriculture is the dominant sector in Germany and Switzerland. Rather surprisingly, from our analysis, the transport sector does not result as the region-averaged dominant sector in any of the selected regions. However, as indicated before, this emission category includes only the tailpipe emissions, neglecting brake wear and re-suspended road dust. This does not preclude that in urban areas and near motorways, road transport is the locally dominant contributor to PM pollution.

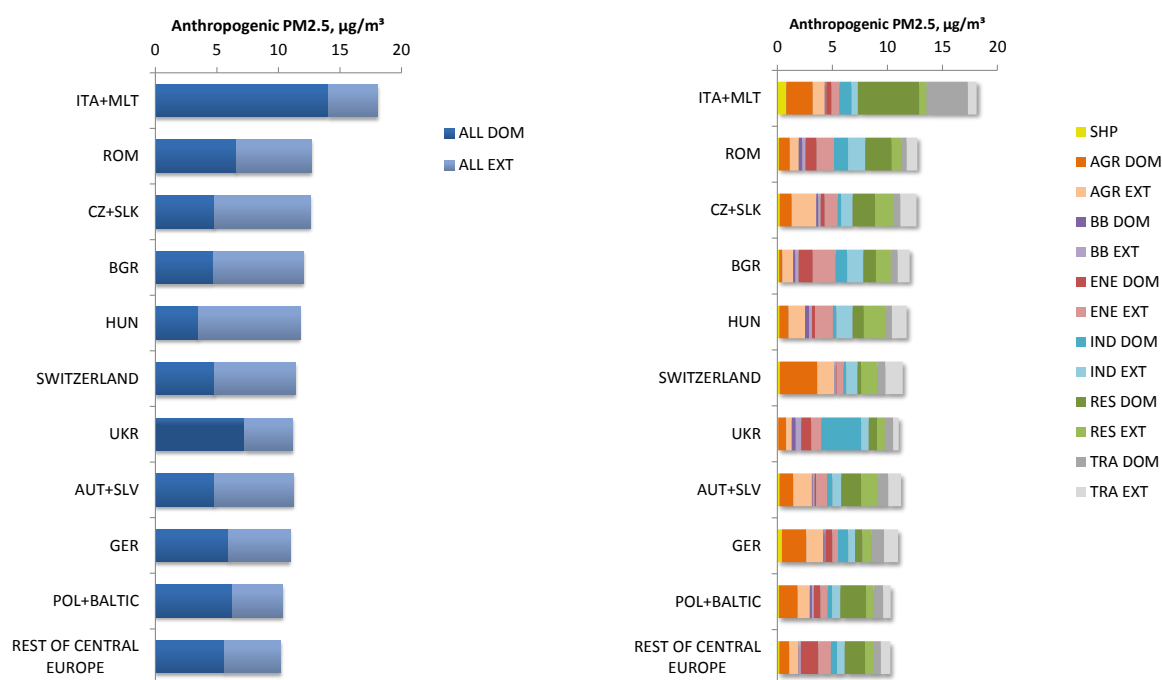


Figure 3: Region-wide annual mean anthropogenic PM_{2.5} concentrations for the Danube basin regions. Both panels show the total PM_{2.5} concentration. Left panel: Dark shade: resulting from domestic emissions, light shade: resulting from emissions external to the region. Right panel: breakdown of PM_{2.5} by emission source. Dark shade: resulting from domestic emissions, light shade: resulting from emissions external to the region. Source categories: SHP= international shipping; AGR = agriculture; BB = large scale biomass burning; ENE = energy production; IND = industrial processes; RES = residential heating; TRA = ground based transport

Year 2010 - PM_{2.5}- induced Premature Mortalities

For the countries belonging to the selected TM5-FASST Danube basin regions, the total number of annual premature mortalities attributable to anthropogenic PM_{2.5} pollution is estimated conservatively to be 136,000 (note that this figure includes mortalities from Baltic States and Malta, which do not belong to the Danube Basin). Figure 4 shows the attribution of the mortalities by sector, by applying the ratios of Table 3 to the total number of mortalities per region, calculated on the basis of exposure to the total anthropogenic PM_{2.5} concentration in that region. The figures are a result of the convolution of pollutant levels with population exposure, and this explains why Germany and Ukraine are among the regions with the highest number of cases. The relative contribution by sector is based on the partitioning by sector for PM_{2.5}. For the whole of the Danube Basin, the residential sector is overall the dominant impacting sector, responsible for 23% of the mortalities. The agricultural sector is second, accounting for 21% of PM_{2.5}-induced premature mortalities, industry for 19%, ground transport for 18%, energy production for 13%, large scale biomass burning from forests for 4% and international shipping for 2%.

Table 3: Fraction of PM2.5 resulting from 'domestic' emissions, and partitioning of PM2.5 over various emission sources.

RECEPTOR REGION	Domes- tic PM2.5	Agric.	Large Scale Brning	Energy Prod.	Industr. Proc.	Resid.	Grnd Trnsp.	Int. Shp.
ITA+MLT	78%	19%	1%	7%	9%	35%	25%	4%
ROM	52%	14%	4%	21%	22%	26%	12%	1%
CZ+SLK	38%	26%	3%	12%	11%	29%	17%	2%
BGR	39%	11%	4%	28%	21%	21%	14%	1%
HUN	30%	20%	4%	16%	15%	26%	16%	1%
SWITZERLAND	42%	44%	1%	6%	11%	16%	20%	2%
UKR	65%	12%	5%	17%	40%	14%	12%	1%
AUT+SLV	43%	26%	2%	10%	12%	30%	18%	2%
GER	54%	34%	1%	11%	14%	13%	22%	4%
POL+BALTIC	61%	27%	3%	12%	11%	30%	15%	1%
REST OF C. EUR.	55%	17%	2%	27%	12%	26%	14%	2%

Annual premature mortalities from PM2.5 , by sector.

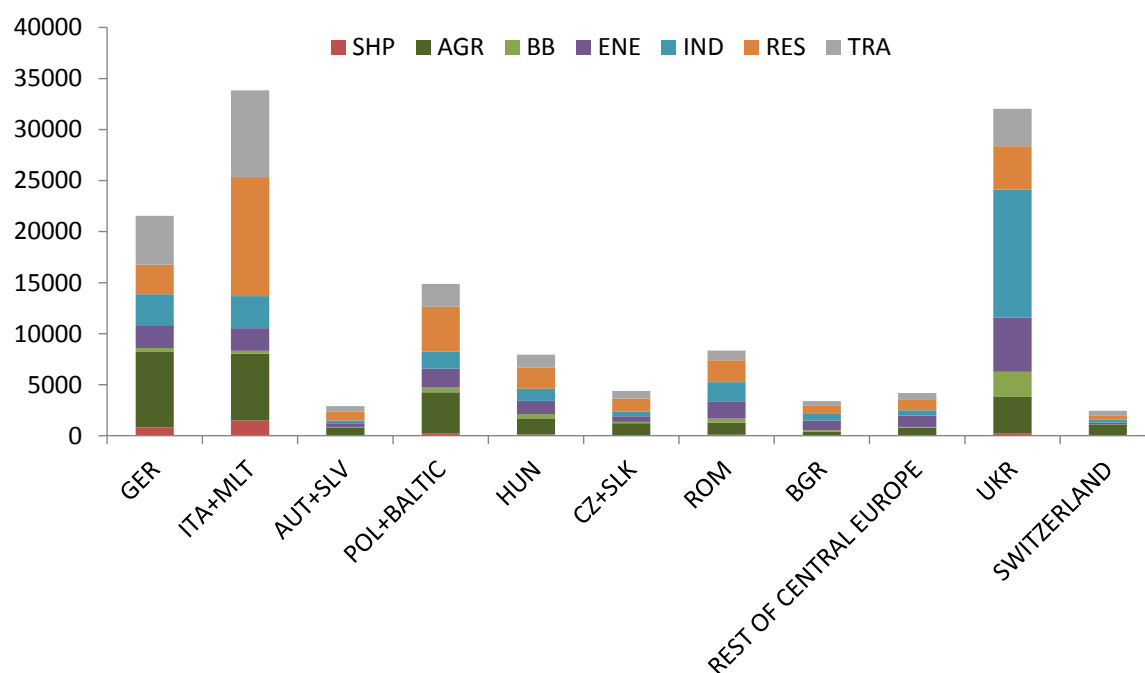


Figure 4: Annual premature mortalities (aged above 30 yr for IHD, stroke, COPD and lung cancer, aged below 5 yr for ALRI) due to anthropogenic PM2.5, for each of the regions and attributed by sector.

Year 2010 - Crop yield losses due to O₃ damage

Ozone is a product from the photochemical reaction of mainly NO_x. The damage caused to crops is estimated by convoluting crop yield data per region with growing season averaged exposure metrics. We estimate the crop yield loss as an average obtained by two different exposure-response functions, the first as a function of AOT40 (accumulated hourly ozone concentrations above 40 ppbV during a 3 months crop growing season), and the second as a function of the 3 month growing-seasonal mean daytime O₃ concentration. Figure 5 shows the resulting absolute yield loss for each of the selected regions with an apportionment by emission category. Road transport and industrial processes (i.e. the major sources for NO_x emissions) are the dominant sectors contributing to O₃ formation and consequently to crop yield losses. Together they account for 60 – 70% of the crop losses in each of the regions considered. Notably, long-range transport of O₃ resulting from international shipping emissions contributes significantly to crop production losses in Italy and Germany. But even in countries without marine coasts, 7% to 15% of the crop losses can be attributed to pollution from international shipping.

Applying producer prices for the year 2008 (FAO statistics), crop losses up to a total estimated annual economic loss for the 4 considered crops of 870 million US\$ for the selected regions.

It has to be kept in mind that these numbers are less robust than it is the case for PM_{2.5} as both O₃ chemistry and the applied concentration-response functions are non-linear. More in particular, depending on the level of NO_x pollution, a reduction in NO_x may cause an increase or decrease in the ozone concentration. The reduced-form TM5-FASST model is not able to capture these non-linearities, including the transition from one NO_x regime to the other. The presented results give a ranking of sectors which are dominating the O₃ pollution levels.

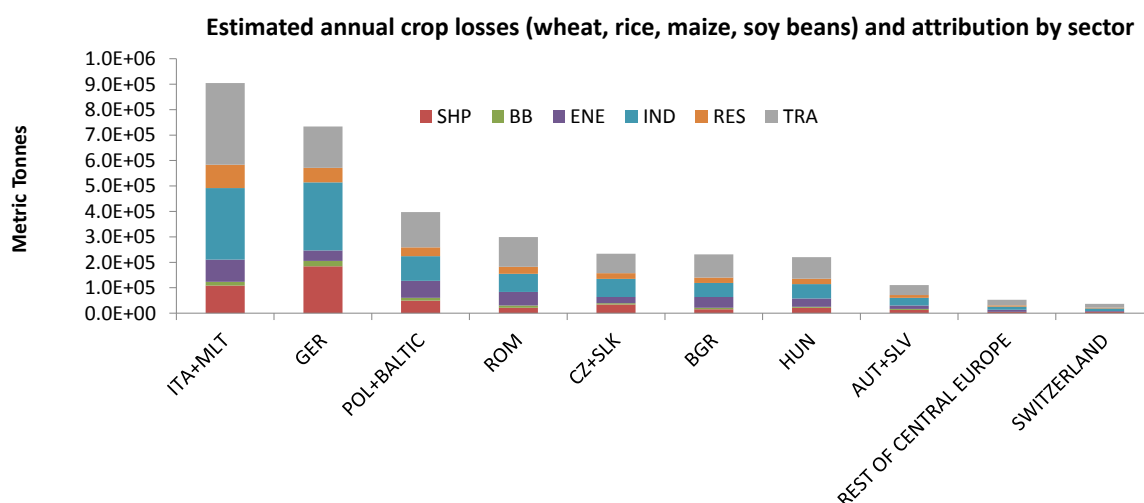


Figure 5: Annual ozone-induced crop losses by region, by sector

Conclusions and work ahead

This report gives the results of an exploratory impact assessment of short-lived air pollutant emissions on human health, crop production and near-term climate with a focus on the Danube basin. We use a global reduced-form source receptor air quality model TM5-FASST and a recent global pollutant emission inventory (HTAP V2, 2014) to make an attribution by sector of the various impacts and to explore the challenges and opportunities for possible. Preliminary results show that trans-boundary pollution is significantly contributing to population exposure to PM_{2.5} in the Danube area. Dominating polluting sectors are the residential sector and agriculture. We estimate that annually 136000 premature mortalities can be attributed to PM_{2.5} pollution in the Danube area, and annual crop losses add up to an economic value of nearly 900 million US\$. This analysis is a first step in a more detailed, country-wise analysis that will be carried out as a follow-up of this report, with an improved version of the model and specifically designed scenarios for the Danube Basin. In particular the resolution over Europe will be increased, making use of EMEP source-receptor grids with a 0.5°x0.5° resolution.

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European Commission

EUR 27068 – Joint Research Centre – Institute for Environment and Sustainability

Title: Preliminary exploratory impact assessment of short-lived pollutants over the Danube Basin

Authors: Rita Van Dingenen, Joana Leitao, Monica Crippa, Diego Guizzardi, Greet Janssens-Maenhout

Luxembourg: Publications Office of the European Union

2015 – 15pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online)

ISBN 978-92-79-45064-8 (PDF)

doi: 10.2788/6207

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